DEPARTMENT OF
CIVIL ENGINEERING

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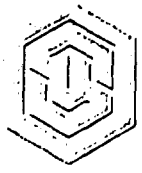
3 March, 1992

Dr. Steven E. Ramberg
Director, Ocean Engineering Division
Department of the Navy, Code 1121
Office of the Chief of Naval Research
800 North Quincy Street
Arlington, Virginia 22217-5000



OREGON
STATE
UNIVERSITY

Apperson Hall 206
Corvallis, Oregon
97331-2302

Dear Steve:

Enclosed please find the final technical report for the ONR-Young Investigator projected "Chaotic and Random Response of Nonlinear Ocean Structural Systems" which ended 31 Dec., 1991.

Oded Gottieb graduated in Dec. and is currently finishing up a couple of papers before going to MIT at the end of this month. I am very glad that he will be working with Prof. Mei, one of the best researcher in the field.

Everything is going very well with the new project. Experiments to validate the analytical models and results have been completed. We are currently doing preliminary documentation and data qualification. We are also making good progress on the stochastic analysis of chaotic systems. Ph.D. student H. Lin has developed a large-scale computer program to calculate the transient and steady state probability density functions (PDFs) governed by the Fokker-Planck equation. A new Ph.D. student, I.M. Shih, has started working on the analysis of stochastic response on the ocean systems to narrow-band excitations. Both students will examine the influence of nonlinear behavior (e.g. bifurcations, and possibly chaos) on the PDF's. A goal of the new project is to examine the extreme value distributions of the nonlinear using both F-P and narrow-band analyses.

I may be visiting the D.C. area in June to attend a National Research Council Ship Structures Committee meeting. I will contact you to arrange a meeting to report further progress on the new project. Thank you very much for your continuing support.

Regards,

Telephone
503-737-4934

Solomon C.S. Yim
Associate Professor

Enclosure
cc: June A Hawley
Defense Technical Information Center

FINAL TECHNICAL REPORT

on

ONR - YOUNG INVESTIGATOR AWARD

RESEARCH PROJECT N00014-88-K-0729

Chaotic and Random Responses of Ocean Structural Systems

Submitted to

Dr. Steven E. Ramberg
Ocean Engineering Division
The Office of Naval Research

by

Solomon C.S. Yim
Ocean Engineering Program
Department of Civil Engineering
Oregon State University
Apperson Hall 202
Corvallis, OR 97331-2302
Telephone: (503) 737-6894 FAX: (503) 737-0485
E-mail: yims@joshua.math.orst.edu

Date: 1 March, 1992

ONR - YOUNG INVESTIGATOR AWARD

RESEARCH PROJECT N00014-88-K-0729

Chaotic and Random Responses of Ocean Structural Systems

Grant Period: 1 Oct., 1988 - 31 Dec., 1991

FINAL TECHNICAL REPORT

Long-Term Goals:

The long-term goals of the research project were to develop a systematic analysis and design procedure for nonlinear ocean structural systems unifying both the deterministic and stochastic approaches. The procedure would provide a basis for: (1) analyzing the system response to combined periodic and stochastic excitations, (2) estimating the likelihood of chaotic response and developing guidelines for field observations, (3) predicting long-term extreme values of chaotic and stochastic responses based on measured data, and (4) ultimately, developing design methods to take into account both chaotic and stochastic behavior of compliant ocean systems.

Near-Term Objectives:

The near-term goals for the research were first to develop and analyze basic nonlinear ocean system models to understand their deterministic chaotic behavior, and then to extend the basic models to include stochastic aspects. The efforts of this ONR-YI research project focused on: (1) developing analytical models of compliant structural systems to understand the physics of chaotic behavior, (2) determining the existence and range of chaotic response of compliant structural systems under combined periodic and stochastic excitations; and (3) validating analytical results experimentally in the O.H. Hindsdale Wave Research Laboratory.

Approach:

The ONR-Young Investigator (ONR-YI) research project was divided into the following tasks, and had been carried out chronologically:

Task 1 — Examine the general system, and its special cases, analytically to determine the existence of chaotic response and the qualitative characteristics of the behavior.

Task 2 — Determine quantitatively the range of environmental conditions for chaotic response using numerical techniques.

Task 3 — Examine the response characteristics of the system subject to random excitations, and superposition of periodic and random excitations with varying relative strength.

Task 4 — Develop analytical tools to identify and distinguish random and chaotic responses, and estimation of their maximum values.

Task 5 — Verify analytical and numerical results obtained in Tasks 1-4 experimentally to develop guidelines for field observation and measurement of chaotic and random responses.

Summary of Results and Accomplishments:

Deterministic analyses (Tasks 1 and 2), including the development of basic mathematical models, derivation of analytical and numerical solution and chaos identification techniques, were completed in 1990. Basic stochastic analyses (Tasks 3 and 4) were completed in 1991. Experiments to verify the analytical and numerical results (Task 5) were conducted at the OSU O.H. Hindsdale Wave Research Laboratory in Dec. 1991.

Systems Considered -- Four basic nonlinear models of ocean structural systems were studied: (1) a taut multi-point cable mooring system [Gottlieb (1991a, b), Gottlieb and Yim (1990, 1991a)], (2) a single-anchor-leg-articulated tower [Gottlieb, Yim and Hudspeth (1991)], (3) an offshore component installation system [Yim and Mha (1991)], and (4) a free-standing offshore equipment system [Lin and Yim (1990), Yim and Lin (1991a,b, c and

d)]. The nonlinearities included large geometry for the multi-point system; large geometry and exact relative-motion Morison drag force for the single-anchor-leg system; bi-linear and dead-band stiffness, and impact for the component installation system; and large geometry and impact for the free-standing equipment system.

Prediction of Chaos -- An efficient systematic analytical procedure was developed to determine the existence and stability of periodic, super-harmonic and sub-harmonic responses, and to predict bifurcations and incipient chaos of nonlinear systems [Gottlieb and Yim (1990, 1991a)]. The procedure employed a combination of harmonic balance, averaging, perturbation, and Floquet stability analysis techniques to identify the regions of periodic and chaotic responses. It was successfully applied to the analysis of the taut multi-point mooring cable and the single-anchor-leg articulated tower systems [Gottlieb and Yim (1991 a, b)]. These systems were found to exhibit local instability and global bifurcations leading to complex nonlinear and chaotic responses. The analytical procedure is completely general and can supplant or significantly reduce the effort of a numerical parametric analysis for most nonlinear ocean systems.

An analytical prediction method based on the Melnikov function was developed for detecting chaotic response of the free-standing equipment system [Yim and Lin (1991d)]. The accuracy of the method was calibrated against other analytical methods and numerical results, and was found to be more accurate than prediction methods developed through perturbation and stability analysis. The Melnikov method successfully identified the major causes of the extreme sensitivity of the free-standing equipment system.

A collection of analytical and numerical tools to identify chaotic response from time series was developed for analytical studies. These tools, used to compute Poincare maps, spectral density functions, Lyapunov exponents, and fractal dimensions of chaotic time series, will also be useful for subsequent research.

Stochastic Characterization of Chaos -- A preliminary study of stochastic properties of time series of (deterministic) chaotic responses of component installation and free-standing equipment systems was performed [Yim and Lin (1990, 1991e, f), and Yim and Mha (1991)]. As anticipated, the amplitude probability density functions of chaotic time histories were found to have a periodic time dependency, thus being non-stationary. However, ensembles of Poincare maps of (deterministic) chaotic responses were found to be ergodic.

The influence of random noise on the stability of chaotic attractors was examined by including an additive white noise to the periodic excitation. Under low noise intensities, chaotic attractors were found to be stable, and the shape of the attractor can be clearly identified. However, with increasing noise intensity, the attractor became fuzzy and eventually became unidentifiable [Yim and Lin (1991d), and Mha (1991)].

Extreme Value Estimations -- To estimate the extreme values of chaotic responses, three practical methods of time series analysis -- direct, Poisson-clumping, and log-fit, were developed [Goulet, et al. (1990), and Yim, et al. (1991, 1992)]. These methods use a sample-scaling technique to overcome the maxima counting and correlation difficulties, but minimize the associated complexity and uncertainties. The direct method removes the dependence on the envelope for maxima estimation. The Poisson-clumping method employs the notion of sample scaling factor but requires neither computing the envelope nor segmenting. Log-fit is a simple logarithm curve fitting, using the slow varying, logarithmic growth property of the expected maximum. The accuracy and the computational efficiency of the methods were found to be superior to Pierce's method. Once probability structures of chaotic responses have been identified, the methods can be applied to estimate their extreme values.

Experimental Verification -- Experiments were conducted in December 1991 at the OSU Wave Research Laboratory. The systems examined consisted of spread-moored spherical buoys. The study included both one-dimensional (1-D) and three-dimensional (3-D) models. Three types of excitations (periodic waves, periodic waves with white noise, and random waves generated from TMA spectra) were used. Results are being analyzed in the continuation research project "Chaotic and Random Responses of Nonlinear Ocean Structural Systems -- Stochastic Analysis and Control". The 1-D results will be used immediately to verify the extensive analytical results obtained from this research project. The 3-D results will calibrate the adequacy of the preliminary Multi-Degrees-of-Freedom (MDOF) models and analytical results, and will be used to guide the development of more sophisticated MDOF models in the continuing research.

Award -- Mr. Oded Gottlieb (Ph.D. student) received the Jefferson Goblet Student Award at the 1991 AIAA Structures, Structural Dynamics & Material Conference with his paper entitled "Bifurcation and Routes to Chaos in

Wave-Structure Interaction Systems."

Continuing Research:

Subsequent research efforts on a continuation project "Chaotic and Random Responses of Ocean Structural Systems: Stochastic Analysis and Control" will focus on: (1) developing and analyzing more realistic models of the compliant structural systems, (2) characterizing and analyzing the probability structure of chaotic response with and without random noise, (3) identifying chaotic response in noisy field data, and (4) predicting long-term extreme values and fatigue behavior of the system to combined periodic and stochastic excitations.

The effects of multi-degree coupling and randomness in the input excitations on the chaotic response will be examined. The focus will be on extending classical nonlinear stochastic analytical methods including Fokker-Planck formulation to directly determine the probability density functions, and stability of nonlinear system response to narrow-band excitations to examine the stochastic behavior of chaotic responses. The experimental results from the original (ONR-YI) research project are essential in guiding the development of the complex MDOF stochastic models and validating the analytical results.

References:

Gottlieb, O., "Bifurcation and Routes to Chaos in Wave-Structure Interaction Systems,"*Proc., AIAA, 32nd Structures, Structural Dynamics and Matl. Conf.*, V.4, 1991a, 2776-2785.

Gottlieb, O., "Nonlinear Oscillations, Bifurcations and Chaos in Wave-Structure Interaction Systems," *Proc., 6th Intl. Workshop on Water Waves & Floating Bodies*, 1991b, 77-80.

Gottlieb, O. and Yim, S.C.S., "Onset of Chaos in a Multi-Point Mooring System," *Proc., 1st European Offshore Mechanics Symposium*, Trondheim, Norway, 1990, 6-12.

Gottlieb, O., Yim, S.C.S., and Hudspeth, R.T., "Analysis of Nonlinear Response of Articulated Towers," *1st Intl. Offshore & Polar Engrg. Conf.*, V.III, Edinburgh, U.K., August, 1991, 384-390; also to appear in *Intl. J. of Offshore and Polar Engineering*.

Gottlieb, O., and Yim, S.C.S., "Nonlinear Oscillations, Bifurcations, and Chaos

in a Multi-Point Mooring System," to appear, *J. of Applied Ocean Research*, 1991a.

Gottlieb, O., and Yim, S.C.S., "Drag-Induced Instability and Chaos in Mooring Systems," submitted for publication, 1991b.

Goulet, M.R., Burton, R.M., and Yim, S.C.S., "On the Extreme Value Estimation," *Report No. OE-90-03*, Oregon State Univ., Ocean Engineering Program, November, 1990.

Lin, H., and Yim, S.C.S., "Chaotic Response and Stability of Offshore Equipment," *Report No. OE-90-02*, Oregon State Univ., Ocean Engineering Program, June, 1990.

Yim, S.C.S., Burton, R.M., and Goulet, M.R., "Practical Methods of Extreme Value Estimation Based on Measured Time-Series for Ocean Systems," *Intl. J. of Ocean Engineering*, accepted for publication, 1991.

Yim, S.C.S., Burton, R.M., and Goulet, M.R., "Extreme Value Estimation Based on Measured Time-Series," *2nd Intl. Offshore & Polar Engrg. Conf.*, to appear, 1992.

Yim, S.C.S., and Lin, H., "Chaotic Behavior and Stability of Free-Standing Offshore Equipment," *Intl. J. of Ocean Engineering*, V.18, N.3, 1991a, 225-250.

Yim, S.C.S., and Lin, H., "Chaotic Response and Stability of Rocking Rigid Objects," *Engineering Mechanics Specialty Conf.*, V.2, Columbus, Ohio, May, 1991b, 791-795.

Yim, S.C.S., and Lin, H., "Chaotic Response and Stochastic Dynamics of Offshore Equipment," *1st Intl. Offshore & Polar Engr. Conf.*, V.III, Edinburgh, U.K., August, 1991c, 420-427.

Yim, S.C.S., and Lin, H., "Nonlinear Impact and Chaotic Response of Slender Rocking Objects," *J. of Engineering Mechanics*, ASCE, V.117, N.9, Sept. 1991d, 2079-2100.

Yim, S.C.S., and Lin, H., "Probabilistic Analysis of a Chaotic Dynamical System," Applications of Chaos, *John Wiley and Sons*, New York, 1991e, (in press).

Yim, S.C.S., and Lin, H., "Chaotic and Stochastic Dynamics of Rocking Objects," submitted for publication, 1991f.

Yim, S.C.S., and Mha, H.S., "Stochastic Analysis of Chaotic Response of Offshore Component Installation Systems," in progress.

LIST OF TECHNICAL REPORTS

PI: SOLOMON C.S. YIM

89-R Yim, S.C.S., "Chaotic and Random Responses of Nonlinear Ocean Structural Systems," *Progress Report 1*, submitted to Ocean Engineering Division, ONR, Dec. 1989.

90-R Yim, S.C.S., "Chaotic and Random Responses of Nonlinear Ocean Structural Systems," *Progress Report 2*, submitted to Ocean Engineering Division, ONR, Dec. 1990.

91-R Yim, S.C.S., "Chaotic and Random Responses of Nonlinear Ocean Structural Systems," *Progress Report 3*, submitted to Ocean Engineering Division, ONR, Dec. 1991.

90-R Lin, H., and Yim, S.C.S., "Chaotic Response and Stability of Offshore Equipment," *Report No. OE-90-02*, Oregon State Univ., Ocean Engineering Program, June, 1990.

90-R Goulet, M.R., Burton, R.M., and Yim, S.C.S., "On the Extreme Value Estimation," *Report No. OE-90-03*, Oregon State Univ., Ocean Engineering Program, November, 1990.

91-R Gottlieb, O., "Nonlinear Oscillations, Bifurcations and Chaos in Ocean Mooring Systems," *Ph.D. Thesis*, submitted to Oregon State University, Dec. 1991.

91-R Mha, H.S., "Stochastic Analysis of Chaotic Response of Offshore Component Installation Systems," *M.S. Report*, Department of Civil Engineering, Dec. 1991.

91-RI Wu, Y-J., "Stochastic Dynamics of Nonlinear Chaotic Systems," *M.S. Report*, Department of Civil Engineering, Dec. 1991.

LIST OF PUBLICATIONS FROM ONR SPONSORED WORK
PI: SOLOMON C.S. YIM

91-P Yim, S.C.S., and Lin, H., "Chaotic Behavior and Stability of Free-Standing Offshore Equipment," *Intl. J. of Ocean Engineering*, V.18, N.3, 1991, 225-250.

91-P Yim, S.C.S., and Lin, H., "Nonlinear Impact and Chaotic Response of Slender Rocking Objects," *J. of Engineering Mechanics*, ASCE, V.117, N.9, Sept. 1991, 2079-2100.

91-P Gottlieb, O., Yim, S.C.S., and Hudspeth, R.T., "Analysis of Nonlinear Response of Articulated Towers," to appear in *Intl. J. of Offshore and Polar Engineering*.

91-P Yim, S.C.S., Burton, R.M., and Goulet, M.R., "Practical Methods of Extreme Value Estimation Based on Measured Time-Series for Ocean Systems," to appear in *Intl. J. of Ocean Engineering*.

91-P Yim, S.C.S., and Lin, H., "Probabilistic Analysis of a Chaotic Dynamical System," to appear in Applications of Chaos, *John Wiley and Sons*, New York.

90-P Gottlieb, O., and Yim, S.C.S., "Nonlinear Oscillations, Bifurcations, and Chaos in a Multi-Point Mooring System," to appear, *J. of Applied Ocean Research*.

90-PS Yim, S.C.S., and Lin, H., "Chaotic and Stochastic Dynamics of Rocking Objects," submitted for publication.

91-PS Gottlieb, O., and Yim, S.C.S., "Drag-Induced Instability and Chaos in Mooring Systems," submitted for publication, 1991b.

90-PI Burton, R.M., Yim, S.C.S., and Goulet, M.R., Comparison of Extreme Value Estimators, 1992.

90-C Gottlieb, O. and Yim, S.C.S., "Onset of Chaos in a Multi-Point Mooring System," *Proc., 1st European Offshore Mechanics Symposium*,

Trondheim, Norway, 1990, 6-12.

91-C Gottlieb, O., "Bifurcation and Routes to Chaos in Wave-Structure Interaction Systems,"*Proc., AIAA, 32nd Structures, Structural Dynamics and Matl. Conf.*, V.4, 1991, 2776-2785.

91-C Gottlieb, O., "Nonlinear Oscillations, Bifurcations and Chaos in Wave-Structure Interaction Systems," *Proc., 6th Intl. Workshop on Water Waves & Floating Bodies*, 1991, 77-80.

91-C Gottlieb, O., Yim, S.C.S., and Hudspeth, R.T., "Analysis of Nonlinear Response of Articulated Towers," *1st Intl. Offshore & Polar Engrg. Conf.*, V.III, Edinburgh, U.K., August, 1991, 384-390.

91-C Yim, S.C.S., and Lin, H., "Chaotic Response and Stability of Rocking Rigid Objects," *Engineering Mechanics Specialty Conf.*, V.2, Columbus, Ohio, May, 1991, 791-795.

91-C Yim, S.C.S., and Lin, H., "Chaotic Response and Stochastic Dynamics of Offshore Equipment," *1st Intl. Offshore & Polar Engr. Conf.*, V.III, Edinburgh, U.K., August, 1991, 420-427.

91-CS Yim, S.C.S., Burton, R.M., and Goulet, M.R., "Extreme Value Estimation Based on Measured Time-Series," *2nd Intl. Offshore & Polar Engrg. Conf.*

SEMINAR AND WORKSHOP PRESENTATIONS

"Chaotic Response and Stability of Offshore Equipment," invited seminar presented at North Carolina State University, Department of Civil Engineering, Feb. 1990.

"Chaotic Response and Dynamic Stability of Slender Rigid Rocking Objects," seminar presented at Oregon State University, Department of Civil Engineering, April 1990 (by H. Lin).

"Chaotic and Stochastic Response of Multi-Point Mooring Systems," invited seminar presented at the Naval Research Laboratory, Center for Advanced Space Sensing, Washington, D.C., Oct. 1990.

"Probabilistic Analysis of a Chaotic Dynamical System," EPRI Workshop on Applications in Chaos, Electric Power Research Institute, San Francisco, California, Dec. 1990 invited speaker.

"Chaotic and Stochastic Dynamics of Free-Standing Offshore Equipment," seminar presented at Oregon State University, Department of Civil Engineering, Feb. 1991.

"Nonlinear Oscillations, Bifurcations and Chaos in Ocean Mooring Systems," seminar presented at Oregon State University, Department of Civil Engineering, Dec. 1991 (by O. Gottlieb).

"Nonlinear Behavior of Offshore Platform Installation Systems," seminar presented at Oregon State University, Department of Civil Engineering, Dec. 1991 (by H-S. Mha).

"Stochastic Dynamics of Nonlinear Chaotic Systems," seminar presented at Oregon State University, Department of Civil Engineering, Dec. 1991 (by Y-J. Wu).

DEGREES GRANTED:

M.S. in Civil Engineering, Mr. H. Lin, June 1990.
M.S. in Mathematics, Mr. M. Goulet, Dec. 1990.
M.S. in Civil Engineering, Mr. H.S. Mha, Dec. 1991
M.S. in Civil Engineering, Mr. Y.J. Wu, Dec. 1991
Ph.D. in Ocean Engineering, Mr. O. Gottlieb, Dec. 1991

HONORS AND AWARDS:

Mr. Oded Gottlieb (Ph.D. student) received the Jefferson Goblet Student Award at the 1991 AIAA Structures, Structural Dynamics & Material Conference with his paper entitled "Bifurcation and Routes to Chaos in Wave-Structure Interaction Systems."

Solomon C.S. Yim (P.I.) was promoted to Associate Professor and granted Indefinite Tenure in 1991.